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RESEARCH MEMORANDUM

ORIGIN AND DEVELOPMENT OF LEADING-EDGE CRACKS IN TURBOJET ENGINE BUCKETS

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NATIONAL ADVISORY COMMITTEE
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ORIGIN AND DEVELOPMENT OF LEADING-EDGE CRACKS IN TURBOJET ENGINE BUCKETS

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SUMMARY

An investigation was conducted to study the origin and development of leading-edge cracking in turbine buckets. Six materials were studied: S-816, M-252, Inconel 550, Inconel 700, Hastelloy R-235, and Jetalloy 1570. A few selected buckets from lots of S-816, M-252, and Inconel 550 were given special stress-relief treatments such as electropolishing, annealing, and reheat treating. The effect of aluminizing S-816 buckets was also investigated. All the buckets were run simultaneously in a J47-25 engine operated in a cyclic manner, 15 minutes at rated speed and approximately 5 minutes at idle.

The results of the investigation indicated that all the materials, as tested, developed leading-edge cracks. The total operating time until the cracks were first detected varied appreciably, ranging from 55 hours for Inconel 550, M-252, and Inconel 700 to 245 hours for Jetalloy 1570. After crack detection, most of the buckets operated well over 100 hours before fracturing. Special treatments such as stress-relief annealing, electropolishing, and reheat-treatment appeared ineffective in improving either the crack or fracture resistance of the specially treated alloys. An analysis of the factors that could affect the development of cracks in turbine buckets (centrifugal stress, vibratory stress, oxidation, and thermal stress) indicates that the probable primary cause was thermal fatigue.

INTRODUCTION

The development of small cracks in many of the jet-engine components exposed to the hot-gas stream is not a new or unusual phenomenon. Frequently cracks have been found in such components as combustion liners, nozzle guide vanes, tailcones, and occasionally in turbine buckets. The nature and causes of cracking in most of these components have been studied and reported in literature. These works are summarized in reference 1.

Generally, the cracks in turbine buckets first appear as very small specks along the leading edge. With continued operation the small specks develop into cracks which appear to be similar to the cracks sometimes found in nozzle guide vanes (fig. 1). These guide-vane cracks are generally believed to be caused by thermal fatigue (ref. 1). The similarity between the cracking in the buckets and in the nozzle guide vanes suggests that the bucket cracking might also be attributed to thermal fatigue. Tests have shown that during starts and stops large thermal gradients are suddenly produced at the leading edges of the buckets (ref. 2). These thermal gradients could cause thermal stress that eventually might cause the leading edge to crack. However, thermal stress might not be the only factor causing the cracks. Still other factors such as centrifugal stress, vibratory stress, residual stress, and oxidation also could conceivably cause or contribute to crack development.

This investigation was conducted to study the origin and development of leading-edge cracks in turbine buckets. Specifically, the aim was to learn when and where the cracks first develop; how long a bucket with cracks would operate before fracturing; whether or not there was a difference in crack resistance among buckets of different high-temperature materials; and what effect several special treatments would have on the crack resistance of buckets.

Six different high-temperature materials were selected for testing: S-816, M-252, Inconel 550, Inconel 700, Hastelloy R-235, and Jetalloy 1570. Some S-816, M-252, and Inconel 550 buckets were given special treatments such as electropolishing, annealing, and reheat treating to reduce fabricational-residual stresses. A few S-816 buckets were aluminized to learn whether this treatment would improve the bucket performance.

A J47-25 engine was selected for this investigation because it is one of several engines in which leading-edge cracks may be produced. Furthermore, this engine is amenable to bucket evaluation, because it has a single-stage turbine, thus reducing the probability of engine damage due to bucket fracture.

MATERIALS, APPARATUS, AND PROCEDURES

Materials

Eight lots (six alloys) of high-temperature materials were studied in this investigation. The materials studied were as follows:

(1) M-252 produced entirely from primary metals (hereinafter called M-252 lot A)

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(2) M-252 produced from a single heat, using a mixture of primary metal and revert scrap (hereinafter called M-252 lot B)

(3) Inconel 550

(4) S-816 randomly selected from a lot of Air Force stock buckets (by chance all were manufactured by one fabricator but were not necessarily from the same heat of material)(hereinafter called S-816 lot A)

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(5) S-816 poured from a single master heat of material (hereinafter called S-816 lot B)

(6) Inconel 700

(7) Hastelloy R-235

(8) Jetalloy 1570

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Chemical Composition

The nominal and actual chemical compositions (wherever available) of the materials tested, as reported by the manufacturer, are presented in table I.

Forging Procedures

All of the buckets, except the S-816 buckets selected from Air Force stock (lot A), were especially forged for this test by a single manufacturer. Four of the materials employed in this investigation (Inconel 550, Inconel 700, Hastelloy R-235, and Jetalloy 1570) were not available as commercially forged alloys, but were specially forged for this evaluation. An outline giving the forging and heat-treating temperatures for all the materials is presented in table II.

Special Treatments

Twelve buckets each of M-252 lots A and B, and S-816 lot B; and eight buckets of both S-816 lot A and Inconel 550 were selected for special treatments as shown in table III. The following treatments were performed:

(1) Electropolishing: Four buckets each of M-252 lot A, M-252 lot B, S-816 lot B, and Inconel 550 were electropolished to remove the surface stresses that may have been produced during the final machining operations (approximately 0.002 in. per surface was removed).

(2) Stress-relief annealing: Four buckets each of M-252 lot A, M-252 lot B, S-816 lot B, and Inconel 550 were annealed at 1500° F to reduce the residual stresses that might have been induced in the buckets during the finishing operations after heat treatment. Specimens were heated to 1500° F slowly and also cooled slowly.

(3) Complete reheat treatment: Four buckets each of M-252 lot A, M-252 lot B, S-816 lot B, and Inconel 550 were completely re-solution-treated and reaged after the buckets were received from the fabricator. This treatment was made to assure stress-relief annealing, which conceivably might not have been accomplished by the stress-relief in item (2).

(4) 100-Hour, repetitive reheat treatment: Four buckets each of M-252 lot B and S-816 lot A were operated for approximately 100 hours, removed and completely reheat-treated (solution treated and aged), then operated again. The procedure was to be repeated after every additional 100 hours of operation until the buckets developed cracks. Reheat treating the buckets was done in an attempt to recover the properties lost because of internal damage engendered during engine operation. The first 112 hours of operation with these reheat-treated buckets were performed in another J47-25 engine, operating with the same conditions as described later in the Engine Operation section. When the 112-hour test was discontinued, the buckets were heat-treated and placed in the engine reported herein.

(5) Aluminizing: Three S-816 buckets selected from Air Force stock were aluminized (aluminum coated and diffusion heat-treated by an aircraft parts manufacturer with experience in this process) to learn if this treatment would improve the cracking resistance of the material. Aluminizing may improve the performance by increasing the reflectivity and thermal conductivity of the bucket, or possibly by altering the physical properties of the surface material.

Inspection

All the buckets were inspected for cracks with fluorescent, post-emulsion oil penetrant before they were used in the test and passed. After every 35 hours of operation at rated speed, the buckets were removed from the engine and again carefully inspected for cracks. Occasionally an inspection would be performed before 35 hours had elapsed if the engine had to be shut down for overhaul because of mechanical difficulties. For each of the test buckets, a record was made at each inspection of the number of cracks (if any), the location of cracks, and the depth of the deepest cracks.

Physical Make-Up of Test Wheel

Ninety-four test buckets and two thermocoupled standard buckets were used in the engine evaluation. All had a J47-25-type configuration. The number of buckets tested for each material and their treatments are presented in table IV. All the buckets were randomly placed around the turbine wheel.

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Temperature and Centrifugal-Stress Distribution

The temperature and centrifugal-stress distribution along the span of a J47-25 bucket operating at full power is shown in figure 2. In the initial stage of the test, the steady-state temperature distribution was obtained by operating, in the engine, buckets equipped with thermocouples located at 1/2-inch intervals along the span of the bucket. More information about the equipment and procedure for making a temperature survey is given in reference 2. The centrifugal-stress distribution was calculated as explained in reference 3.

Critical Cross Section

The critical cross section of a bucket is usually considered to be the section of the bucket that would be most likely to fail if temperature and centrifugal stress were the only cause of failure. It is determined by applying previously determined data for stress and temperature distribution in the bucket to the stress-rupture data for the material, and then finding the expected life of the material at several points along the span. The cross section with the lowest expected life is the critical cross section.

For example, for an S-816, J47-25 bucket, this critical cross section is 1.6 inches from the base, and the theoretical life of the material at this section is about 13,000 hours (fig. 3). These calculations were based on bar-stock stress-rupture data for 1300°, 1400°, and 1500° F. Simple interpolations were used to determine the intermediate isothermal-stress values, and straight-line extrapolations were used to approximate the expected life above 1000 hours. While straight-line extrapolations introduce inaccuracies, they do offer a means of obtaining order-of-magnitude values.

As will be shown later, the actual bucket lives were only a few hundred hours, much less than the predicted life of 13,000 hours. Since the differences are so great, even large inaccuracies of several thousand hours in the predicted life calculations would not affect the conclusions that will be reached.

The stress-rupture values for the other five materials are generally higher than for S-816; therefore, the minimum theoretical life for these alloys would be expected to be greater than the 13,000-hour value for S-816 shown in figure 3. A detailed explanation of the procedure used for determining the location in the bucket of the critical cross section is given in reference 4.

Engine Operation

The J47 engine was operated in cycles of 20 minutes duration; 15 minutes at maximum rated speed (7950 rpm) and about 5 minutes at idle speed (3000 rpm). The engine was started and stopped, accelerated and decelerated in a normal manner, which should produce temperature gradients within the buckets equivalent to those reported in reference 2. Engine operation was interrupted for routine maintenance, to replace fractured buckets, and to shut down at the end of each work day. Fractured buckets were replaced with standard S-816 buckets.

When the engine was operating at rated speed (7950 rpm), the centrifugal stress at the critical cross section in the bucket was about 13,000 pounds per square inch. The bucket temperature at this point was 1455° F (tailpipe temperature, 1275° F). Periodically the bucket temperature was checked with the aid of thermocouples mounted in two buckets.

The test was discontinued after the engine had been operated for a total of 500 hours at full power.

Macroexamination of Failed Buckets

Buckets were classified in two ways, cracked or fractured. The cracks could range in size from those barely visible to the eye to those over 1/2 inch deep. A fractured bucket was a bucket that actually ruptured during operation. The remnants of the fractured buckets, particularly the fracture surfaces, were macroexamined to determine the type and origin of the failure. Photographs were taken of typical fractures for most of the materials.

Metallographic Studies of Operated and Failed Buckets

Metallographic studies were performed on 17 of 35 buckets that fractured and 12 unfractured buckets that had operated 500 hours. The numbers of buckets microexamined and their conditions are presented in table V.

Metallographic work was performed to determine the nature of the leading-edge cracks and to observe any unusual appearances in the structure of the materials. Microspecimens were taken from regions in the buckets where the cracks appeared and where the fractures originated. Standard metallurgical procedures were used in preparing the specimens.

RESULTS

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Development of Leading-Edge Cracks

The first leading-edge cracks were detected when some thermocouples had to be replaced after 55 hours of operation. At this time, 22 buckets had leading-edge cracks. By the end of the test (500 hr), 92 of the 94 test buckets had cracked.

Generally, the development of the leading-edge cracks followed a pattern which could be discerned over several consecutive Zyglo inspections. At first, a few very small cracks would appear in the vicinity of the critical cross section of the bucket. With continued operation, additional cracks would develop above and below this region. After about 100 hours of operation, a bucket that had cracked would have between 5 and 30 small cracks located between 0.9 and 2.9 inches above the base. Most of the cracks grew to about 1/32 to 1/8 inch in depth, then stopped growing. However, sometimes one or two of the cracks would continue to grow and cause the bucket to fracture.

Two different types of crack propagation that occur in buckets are shown in figure 4. In the bucket shown in figure 4(a)(Inconel 550), the cracks were first detected during the 55-hour inspection. The cracks propagated at a moderate rate for the next 200 hours but then slowed to such a slow rate that the bucket was still operating when the test was discontinued after 500 hours. In contrast to the bucket shown in figure 4(a) is the bucket in figure 4(b)(S-816 bucket). This bucket developed only a few cracks by 55 hours. However, two of these cracks grew very quickly, and within 120 hours one of these two cracks was nearly 1/2 inch deep. For the next 125 hours the cracks hardly grew, until finally at 306 hours the bucket fractured.

Development of Bucket Fractures

Table VI shows data for all the fractured buckets: the time when the cracks were first detected, the time when the buckets fractured, the time differential between crack detection and fracture, and the fracture location. A total of 35 fractures had occurred when the test was terminated. The first fracture occurred after 218 hours of operation. All the bucket fractures that occurred during the test began as leading-edge cracks.

The minimum time differential between crack detection and bucket fracture was 92 hours. All the other time differentials were above 120 hours. The bucket fractures all began in the region 1.1 to 2.2 inches from the base of the bucket, with the largest number of fractures occurring at 1.3 inches.

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Comparison of Performance for the Materials Tested

All the materials tested were compared on the basis of resistance to cracking and resistance to fracture. First, a comparison will be made of the as-received materials (fig. 5). Then, a comparison will be made of the groups of buckets that received special treatments (fig. 6).

Performance of as-received buckets. - All the lots of as-received materials developed cracks before 245 hours of operation at rated speed as shown in figure 5. In three of these materials, M-252 lot A, Inconel 550, and Inconel 700, cracks were detected as early as 55 hours. The two materials that displayed the best resistance to cracking were Jetalloy 1570 and S-816 lot A. Cracks were first noted in Jetalloy 1570 at 245 hours. Although one of the S-816 lot A buckets showed cracks at 55 hours, this short time to cracking was so far outside the scatter band for the material that it could not be considered a representative bucket. For the remainder of the buckets of the S-816 lot A group no cracks were observed until 312 hours of engine operation.

The first fracture of an as-received material occurred at 218 hours to an S-816 lot B bucket. At the termination of the test (500 hr), the three materials that had no fractures were Inconel 550, Inconel 700, and Jetalloy 1570. It is interesting to note that two of these, Inconel 550 and Inconel 700, were among the first to crack.

Performance of specially treated M-252 buckets. - The crack resistance and service-life performances for all the groups of both M-252 lot A and M-252 lot B were very similar (figs. 6(a) and (b)). When compared on the basis of average time to cracking, all the groups (as-received, electropolished, annealed, and reheat-treated) for both materials cracked at about the same time, approximately 125 hours.

Bucket fracture occurred in all groups of M-252 during the test. The first fractures for all groups of lots A and B occurred between 290 and 330 hours except the annealed M-252 lot B group, which had its first fracture a little later at 395 hours.

Performance of 100-hour, repetitive heat-treated M-252 lot B buckets. - The four M-252 lot B buckets, reheat-treated (completely solution treated and aged) after every 100 hours of operation, developed cracks about the same time as the untreated buckets (approximately 175 hr), as shown in figure 6(c). At 500 hours, three of the repetitive reheat-treated buckets had fractured as compared with only one fractured as-received bucket. Since the repetitively heat-treated buckets cracked before the second scheduled heat treatment, they received only one reheat treatment.

Performance of specially treated Inconel 550 buckets. - All the groups of the specially treated and as-received Inconel 550 buckets had cracks at 55 hours as shown in figure 6(d). None of the groups had fractured buckets when the test was discontinued after 500 hours of operation.

Performance of specially treated S-816 lot B buckets. - All the specially treated S-816 lot B buckets displayed slightly better performance than the as-received buckets of the same lot. These as-received buckets had the least resistance to cracking of any of the S-816 buckets tested, displaying cracks at 80 hours. The crack resistance of the electropolished and annealed groups was about the same; both developed cracks at about 140 hours. The reheat-treated group showed the best performance, not cracking until 175 hours.

All the groups had an average fracture time of about 325 hours except the reheat-treated, which did not have any fractures until after 400 hours.

Performance of aluminized S-816 lot A buckets. - The crack resistance of the aluminized S-816 lot A buckets was below that of the as-received S-816 lot A buckets (fig. 6(f)). All the aluminized buckets showed cracks at 55 hours, while all but one (a nontypical bucket) of the as-received buckets did not begin to show cracks until after 300 hours.

The resistance to fracture of the aluminized buckets was below that of the as-received buckets. The two aluminized buckets that remained in the engine after the 244-hour inspection fractured before 350 hours, while only one of the seven as-received buckets had fractured during 500 hours of operation. This bucket was the S-816 bucket which was considered nonrepresentative.

Performance of 100-hour, repetitively heat-treated S-816 buckets. - All the S-816 lot A buckets reheat-treated after every 100 hours of operation developed cracks between 350 and 400 hours of operation. Their crack resistance was about equal to the as-received buckets (fig. 6(g)). The reheat-treated buckets were heat-treated a total of three times.

Macro- and Microexamination of Unfractured Buckets

Fifty-nine of the buckets ran the full 500 hours without fracturing. Fifty-seven of these buckets had leading-edge cracks. (Two S-816 lot A buckets did not have cracks.) Figure 7 is a set of photographs taken after 500 hours of operation showing seven typical unfractured buckets with leading-edge cracks. Each bucket is a different as-received material. These photographs in figure 7 were taken with an ultraviolet light after the buckets were given a Zyglo treatment. During the $1\frac{1}{2}$ hour exposure time, the Zyglo oil bled from the cracks, producing the blotchy effect seen in the photographs.

Microexaminations were performed on the leading-edge regions of the 29 buckets enumerated in table V to determine the nature of the leading-edge cracks. In almost every instance, the cracks appeared to be intergranular. Figure 8 shows photomicrographs of typical leading-edge cracks as they occurred in the unfractured buckets shown in figure 7. In all these photographs, the surrounding structures appear normal for the material.

Of all the buckets examined, the only bucket with the slightest indication of abnormal structure was an S-816 lot B bucket (fig. 9). The small dark areas in the grain boundaries may have been caused by vacancy migrations. Some of the cracks that ultimately developed in the area were lined with oxides.

Figure 10 is a photograph of a leading-edge crack in an S-816 lot B bucket, which appears to be transgranular. This particular crack was the only definite transgranular leading-edge crack found during the microexaminations.

One of the aluminized S-816 buckets was removed from the wheel before it fractured (after 244 hr of operation), and a section was taken of the leading edge to determine whether the cracks penetrated beyond the aluminum coating. Figure 11(a) is a photomicrograph of the leading-edge region shown in figure 11(b). The photomicrograph shows diffusion has taken place between the aluminum coating and the base metal. The cracks did not extend beyond the diffusion zone (fig. 11(a)).

Macro- and Microexamination of Fractured Buckets

All the buckets that fractured were visually examined to locate the origin of the fracture. The examinations disclosed that all the fractures began at the leading edges of the buckets. The zone where the fracture began always had the rough appearance of an intergranular stress-rupture-type failure. The zone adjacent to the fracture origin had a concentric-ring appearance typical of a fatigue failure, or in a few cases, a rough, slightly discolored appearance typical of a stress-rupture failure. When the cracks propagated deeply enough (usually across about one-third of the bucket chord), the centrifugal force on the bucket caused it to fail in tension.

Figure 12 shows the photographs of typical fractured untreated (as-received) buckets of S-816 (fig. 12(a) and (b)), M-252 (fig. 12(c) and (d)), and Hastelloy R-235 (fig. 12(e)). None of the other materials tested incurred fractures during the test.

Microsections of 17 of the 35 fractured buckets were taken from the regions where the fractures occurred. Usually the region very close to the leading edge of the buckets appeared so oxidized that it was difficult to determine whether the fracture began as a transgranular or intergranular failure. In a few buckets, the region was not too badly damaged by oxidation, and the fracture origin appeared to be intergranular in nature. Figure 13 is a photomicrograph of the region where the fracture began in a Hastelloy R-235 bucket. The intergranular cracks in this Hastelloy R-235 bucket soon changed to transgranular and propagated as a transgranular crack for about 1/2 inch. Another example of a fracture changing from intergranular to transgranular, this time in an M-252 bucket, is shown in figure 14.

DISCUSSION OF RESULTS

The results of the investigation showed that all the high-temperature materials studied were subject to leading-edge cracking. The total operating time until the cracks were first detected varied appreciably among materials, ranging from 55 hours for Inconel 550 to 245 hours for Jetalloy 1570. The resistance to fracturing also varied appreciably between materials with two of the alloys, Inconel 550 and Inconel 700, not incurring any fractures before the test was discontinued, while other alloys fractured as early as 218 hours. Since some of the materials tested were experimentally forged, the fabricational techniques used in producing the buckets may not have been fully developed to the point where they could produce the best engine results. Therefore, caution should be observed in comparing the performance of the materials.

Although the results of this investigation did not conclusively define the mechanism by which the cracks originated, some insight into the mechanism may be obtained by a systematic analysis of the factors that influence turbine-bucket failure during operation. In this analysis such factors as centrifugal stress, vibratory stress, fabricational residual stress, thermal stress, and oxidation will be considered.

If the centrifugal stress operating on the buckets at the elevated temperatures were an important factor that contributed to the formation of the cracks, it would be expected that the cracks would have formed only in the critical zone. However, cracking was not limited to the critical zone; it also occurred in regions where the combination of centrifugal stress and temperature was rather low. In addition, calculations indicate that if centrifugal stress and temperature were the only factors causing the cracks, the buckets should have been free from cracks for almost 13,000 hours (fig. 2). Since the cracks formed in a small fraction of this time, it is most likely that some factors other than centrifugal stress were the primary cause of the cracking. 4219

Vibrational fatigue was another factor that did not appear to influence crack formation significantly. Generally, mechanical fatigue fractures are transgranular (but not always, ref. 5) and occur as a single fracture. The cracks obtained in the test were predominantly intergranular and in practically every case a multiplicity of cracks existed. If vibrational fatigue were an important factor, only a single crack would have been expected to develop in each bucket. While vibrational fatigue does not appear to play an important role in the formation of the cracks, it is important in propagation of the cracks as shown by the fact that most of the fractures (a few M-252 buckets were exceptions) propagated as transgranular failures with the concentric-ring appearance typical of a vibrational-fatigue fracture.

Fabricational-residual stress also did not appear to be a direct contributing factor in the formation of leading-edge cracks. If it had been a direct factor, the bucket lots treated to remove the residual stress (electropolished, annealed, and reheat-treated) should have shown a significant improvement in crack resistance as compared with the untreated buckets. The tests showed very little, if any, improvement in crack resistance for all the bucket lots that received treatments, except possibly for a single group of S-816 reheat-treated buckets. It is possible that fabricational practices play a more important role than may be apparent from the test results. The physical properties of the alloys could have been so badly damaged during forging that no amount of heat treatment could improve the properties. If this were the case, the heat treatments tried could have been ineffective in removing the damage done by fabrication.

Metallographic evidence indicates that most of the cracks were intergranular and that oxidation was present along the interface of the cracks. There is no way of telling whether oxidation occurred before or after the cracks formed. In only one of the buckets examined (an S-816 bucket) was there an indication that intergranular oxidation may have taken place (fig. 9). There is a possibility that the unusual structure (the dark areas at the grain boundaries) surrounding the large oxidation concentrations shown in figure 9 may not be caused by oxidation, but rather is a result of the migration of vacancies from the matrix to localized areas in the grain boundaries (ref. 6).

The preceeding process of elimination leads us to the conclusion that the factor appearing to exert the most significant influence on crack formation is thermal stress. These thermal stresses are caused by thermal gradients that occur in the bucket during cycling, acceleration and deceleration. In another NACA engine program (unpublished) actual measurements have shown that temperature differentials of 240° F during starts and 90° F during stops exist at the leading edge between
4219 the skin and a region 0.05 inch beneath the skin. This is equivalent to a gradient of 4800° F per inch during starts and a thermal gradient of 1800° F per inch during stops. Preliminary calculations of the stress that would be formed in the leading-edge regions during starts indicate that large enough stresses could be formed to cause plastic flow in the material during the first start. Repeated thermal stressing of the material during subsequent starts and stops could cause additional plastic flow, which would damage the physical properties of the material and eventually lead to crack formation by the mechanism of thermal fatigue. All these data and calculations support the concept that the cracks could be caused by thermal stress.

However, the fact that the cracks were intergranular instead of transgranular, and that the locations of the first cracks were generally near the critical cross section instead of the cross section where the maximum bucket temperature occurred could raise a degree of doubt as to the importance of thermal stress as a primary factor. While it might be expected that thermal-fatigue-type cracks would be transgranular, the magnitude and rate of application of the thermal stresses along with the corrosive atmosphere could conceivably cause an intergranular type of fracture. The fact that the location of the first cracks was near the critical point does not necessarily eliminate thermal stress as the prime cause of the cracks. It is possible that the maximum transient thermal gradients do not occur where the maximum steady-state bucket temperatures are located, but rather at some lower location in the bucket. In conclusion, it is believed that the primary cause of the cracks appears to be repeated thermal stress or thermal fatigue. The remaining factors, centrifugal stress, vibrational stress, residual stress, and oxidation, probably contribute to the cracking; in fact, they may be necessary to effect the cracking, but nevertheless, they appear to be of secondary importance.

One of the important phenomena noted during the investigation was the slow rate of crack propagation in the buckets. Usually, the buckets would operate 100 hours or more at full power after crack detection before they would fracture (shown previously in table VI). For example, in the case of Inconel 550, the cracks propagated so slowly that none of the buckets fractured before the test was discontinued after 500 hours, even though all the buckets were cracked at 55 hours. In contrast with the Inconel 550 performance is the performance of an S-816 lot B bucket which fractured within 92 hours after the cracks were first detected. Although the performance of this S-816 lot B bucket was very poor as compared with most S-816 buckets, the 92-hour period is a substantially safe period during which the cracks could have been detected. There is a small chance that the cracks could have occurred and the bucket fractured between the major inspection periods performed every 100 hours. However, in considering that all the other buckets that fractured operated well over 100 hours after crack detection, the chances that any one bucket would have both developed cracks and fractured between inspections is quite small. A direct comparison between the data contained herein and what would be expected in actual service cannot be made because the operating conditions of one (the number of starts and stops, the time at max. rated speed, etc.) are probably quite different from the conditions of the other. In all probability, the engine test conditions reported would be as severe as those encountered in actual service, or more severe.

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It might be well to emphasize that although repeated thermal stressing is probably the cause of leading-edge cracking, repeated thermal stressing alone will not cause complete bucket fracture. The leading-edge cracks must be propagated by creep rupture or fatigue. A long safety period between crack initiation and bucket fracture is possible if the bucket is designed for very long stress-rupture life in relation to required service life, and if the vibratory stresses are low.

SUMMARY OF RESULTS

The results of the investigation into the development of leading-edge cracks occurring in turbojet turbine buckets are summarized as follows:

1. All the materials tested (S-816, M-252, Inconel 550, Inconel 700, Hastelloy R-235, and Jetalloy 1570) developed leading-edge cracks during cyclic engine operation. The total operating time until the cracks were first detected varied appreciably among materials, ranging from 55 hours for Inconel 550, M-252, and Inconel 700 to 245 hours for Jetalloy 1570.

2. The principal factor contributing to the formation of leading-edge cracks in the buckets appeared to be thermal stress. Centrifugal stress, vibrational stress, fabricational-residual stress, and oxidation are probably of secondary importance to the mechanism of crack formation. Vibrational stress (fatigue) appeared to be the principal mechanism in the propagation of the cracks.

3. The minimum time between crack detection and bucket fracture was 92 hours. In most cases, the chances that the cracks would have been discovered and the buckets removed during a 100-hour inspection are very good. A direct comparison between these results and what would be expected in actual service cannot be made, because the operating conditions are probably quite different. Probably, the engine test conditions are more severe than actual service conditions.

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4. None of the electropolishing, stress-relief annealing, reheat, or repetitive reheat treatments appeared effective in improving the resistance of these materials to edge cracking or fracturing. Aluminizing of S-816 buckets also did not appear to improve resistance to edge cracking or fracturing.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 15, 1957

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TABLE I. - CHEMICAL COMPOSITION OF MATERIALS TESTED

		C	Cr	Ni	Co	Mo	W	Fe	Cb	Ti	Al	B	Cu	Mn	Si
S-816 lot A (Air Force stock)	Nominal	0.4	20	20	44	4	4	2.8	3.75	----	----	--	----	----	----
	Actual	----	-----	-------	-------	-----	----	-----	----	----	----	--	----	----	----
S-816 lot B (single heat)	Nominal	0.4	20	20	44	4	4	2.8	3.75	----	----	--	----	----	----
	Actual	0.35	19.72	19.66	Balance	4.11	3.60	2.75	3.79	----	----	--	----	1.42	0.43
M-252 lot A (virgin metal)	Nominal	0.1	19	53.5	10	10	----	2	----	2.5	0.75	--	----	----	----
	Actual	1.13	19.50	Balance	10.25	10.11	----	1.85	----	2.30	0.85	--	----	1.15	0.65
M-252 lot B (revert scrap)	Nominal	0.15	19	53.5	10	10	----	2	----	2.5	0.75	--	----	----	----
	Actual	0.13	20	Balance	12.60	9.45	----	2.62	----	2.32	0.78	--	----	0.78	0.43
Inconel 550	Nominal	0.06	15	73	-------	-----	----	7	0.9	2.5	1.2	--	----	----	----
	Actual	0.04	15.39	72.18	-------	-----	----	6.79	0.87	2.54	1.10	--	0.05	0.68	0.33
Inconel 700	Nominal	0.1	15	50	27	3	----	----	----	2.3	3	--	----	----	----
	Actual	0.10	19.90	48.74	Balance	2.92	----	0.48	----	2.22	2.85	--	----	0.07	0.12
Hastelloy R-235	Nominal	0.15	15.5	62	2.5	5.5	----	10	----	2.5	2.0	--	----	----	0.6
	Actual	----	-----	-------	-------	-----	----	-----	----	----	----	--	----	----	----
Jetalloy 1570	Nominal	0.2	20	30	39	-----	6.5	-----	----	4	----	--	----	----	----
	Actual	----	-----	-------	-------	-----	----	-----	----	----	----	--	----	----	----

TABLE II. - FORGING PROCEDURES AND HEAT TREATMENTS

Material	Forging temperature, °F	Heat treatment								
		Solution treatment			First age			Second age		
		Temperature, °F	Time, hr	Quench	Temperature, °F	Time, hr	Quench	Temperature, °F	Time, hr	Quench
S-816 lot A (Air Force stock)	----	----	-	---	----	--	---	----	-	---
S-816 lot B (single heat)	2100	2150	1	[a]WQ	1400	12	[b]AC	----	-	---
M-252 lot A (virgin metal)	2000	1950	4	[b]AC	1400	15	[b]AC	----	-	---
M-252 lot B (revert scrap)	2000	1950	4	[b]AC	1400	15	[b]AC	----	-	---
Inconel 550	2150	2150	1	[b]AC	1600	4	[b]AC	1350	4	[b]AC
Inconel 700	2100	2150	2	[b]AC	1600	4	[b]AC	----	-	---
Hastelloy R-235	2000	2150	1	[b]AC	1650	4	[b]AC	----	-	---
Jetalloy 1570	2000	2150	4	[b]AC	1650	24	[b]AC	----	-	---

[a]Water-quenched.

[b]Air-cooled.

TABLE III. - SPECIAL TREATMENTS RENDERED SOME S-816, M-252, AND INCONEL 550 BUCKETS

Material	Electropolished group amount of surface removed, in.	Stress-relief annealed group			Reheat-treated group									100-Hr repetitive heat-treated group	Aluminized group		
					Solution treatment			First age			Second age				Coating temperature, °F	Diffusion	
		Temperature,[a] °F	Time, hr	Quench	Temperature, °F	Time, hr	Quench	Temperature, °F	Time, hr	Quench	Temperature, °F	Time, hr	Quench			Temperature, °F	Time, hr
S-816 lot A (Air Force stock)	-----	----	-	---	----	-	---	----	--	---	----	-	---	-------------	1350	(b)	(b)
S-816 lot B (single heat)	0.002	1500	1	[c]AC	2150	1	[d]WQ	1400	15	[c]AC	----	-	---	Same procedure as reheat-treated S-816, lot B	----	---	---
M-252 lot A (virgin metal)	0.002	1500	1	[c]AC	1950	4	[c]AC	1400	15	[c]AC	----	-	---	-------------	----	---	---
M-252 lot B (reheat scrap)	0.002	1500	1	[c]AC	1950	4	[c]AC	1400	15	[c]AC	----	-	---	Same procedure as reheat treated	----	---	---
Inconel 550	0.002	1500	1	[c]AC	2150	1	[c]AC	1600	4	[c]AC	1350	4	[c]AC	-------------	----	---	---

[a]Buckets inserted in cold furnace. Temperature increased 300° F/hr until 1500° F.

[b]Unknown.

[c]Air-cooled.

[d]Water-quenched.

TABLE IV. - PHYSICAL MAKEUP OF TEST WHEEL

[All the buckets tested were randomly placed around the turbine wheel.]

	Total number of buckets tested					
	As-received	Electro-polished	Stress-relief annealed	Reheat-treated	100-Hr reheat-treated	Aluminum coated
S-816 lot A	7	-	-	-	4	3
S-816 lot B	4	4	4	4	-	-
M-252 lot A	4	4	4	4	4	-
M-252 lot B	4	4	4	4	-	-
Inconel 550	4	4	4	4	-	-
Inconel 700	4	-	-	-	-	-
Hastelloy R-235	4	-	-	-	-	-
Jetalloy 1570	4	-	-	-	-	-

TABLE V. - MICROEXAMINED BUCKETS

Material	Treatment	Condition after operation	Number examined
S-816 lot A	As received As received Aluminum coated	Not fractured Fractured Not fractured	1 1 1
S-816 lot B	As received Electropolished Annealed Reheat treated Heat treated	Fractured Fractured Fractured Not fractured Fractured	3 2 1 1 1
M-252 lot A	As received As received Annealed Reheat treated	Not fractured Fractured Fractured Fractured	1 2 1 1
M-252 lot B	As received As received Electropolished Electropolished Annealed Annealed 100-Hr repetitive heat treated	Not fractured Fractured Fractured Not fractured Not fractured Fractured Fractured	1 1 1 1 1 1 1
Inconel 550	As received Annealed	Not fractured Not fractured	1 1
Inconel 700	As received	Not fractured	1
Hastelloy R-235	As received As received	Not fractured Fractured	1 1
Jetalloy 1570	As received	Not fractured	1

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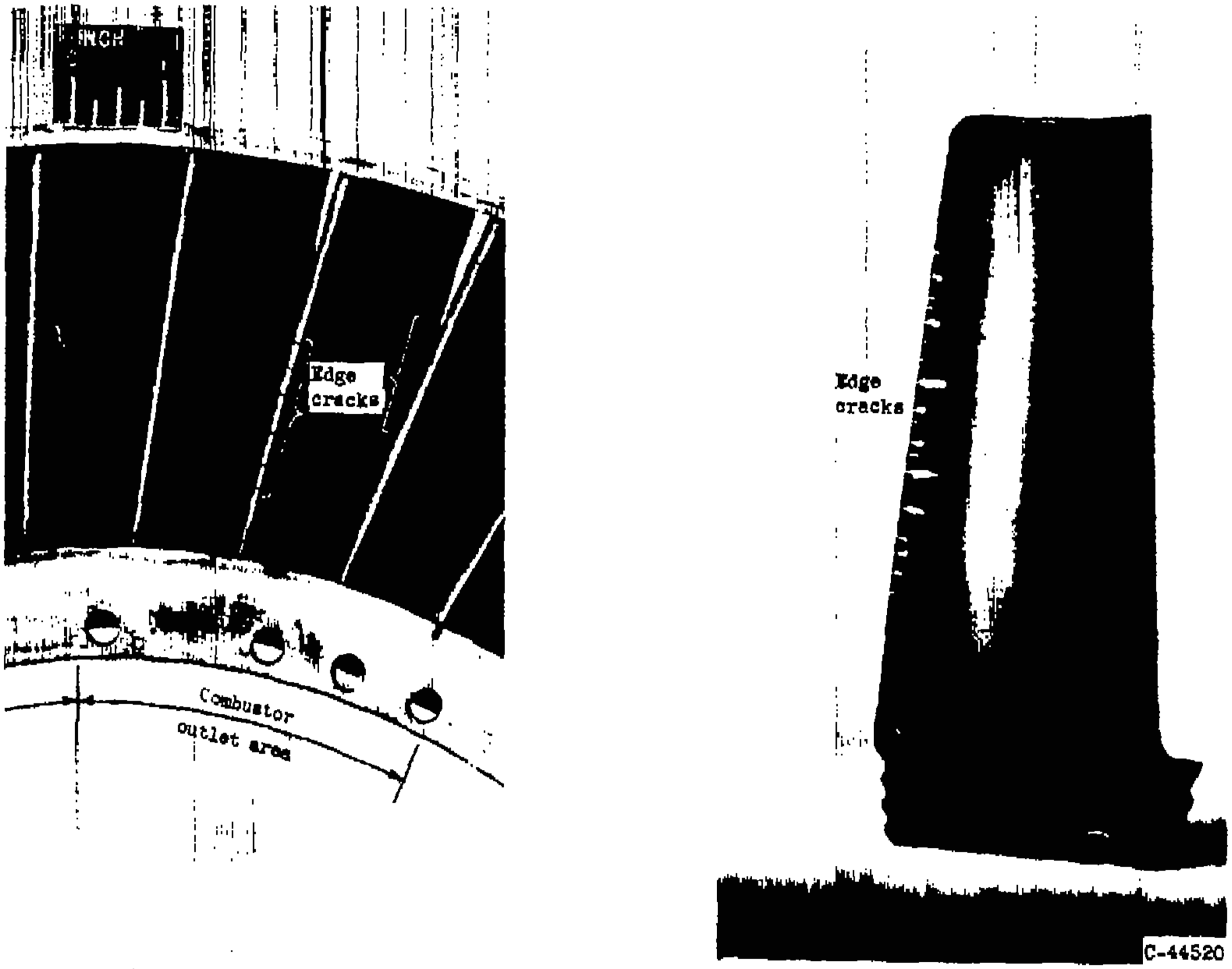
TABLE VI. - DATA FOR FRACTURED BUCKETS

Material	Time to crack detection, hr	Time to fracture, hr	Time between cracks and fractures, hr	Fracture location, in. above base platform
S-816 lot A:				
As received	55	306	241	2.2
Aluminized	55	285	165	1.6
Aluminized	55	316	196	2.2
S-816 lot B:				
As received	80	218	138	1.6
As received	106	254	148	1.8
As received	106	335	229	1.2
As received	140	430	291	1.9
Stress-relief annealed	140	264	124	1.4
Stress-relief annealed	140	302	162	1.6
Stress-relief annealed	244	336	92	1.2
Stress-relief annealed	210	413	203	1.4
Electropolished	175	299	124	1.4
Electropolished	175	315	140	1.3
Electropolished	140	331	191	1.4
Electropolished	210	341	131	1.3
Reheat treated	175	407	232	1.3
Reheat treated	244	426	182	1.4
M-252 lot A:				
As received	175	330	155	1.6
Stress-relief annealed	80	389	309	---
Stress-relief annealed	80	434	354	1.8
Stress-relief annealed	210	471	261	---
Electropolished	106	312	206	1.2
Electropolished	80	440	360	1.9
Reheat treated	175	309	134	1.3
100-Hr repetitive heat treated	168	444	276	1.2
100-Hr repetitive heat treated	168	446	278	1.3
100-Hr repetitive heat treated	168	451	283	1.2
M-252 lot B:				
As received	55	300	245	1.1
As received	80	326	246	1.3
Stress-relief annealed	80	289	209	1.4
Stress-relief annealed	106	337	231	1.5
Electropolished	175	319	144	1.7
Electropolished	80	326	256	1.4
Reheat treated	80	323	243	1.5
Hastelloy R-235				
As received	106	312	206	1.3



(a) Nozzle guide vanes.

(b) Turbine bucket.

Figure 1. - Edge cracks in nozzle guide vanes and a turbine bucket.

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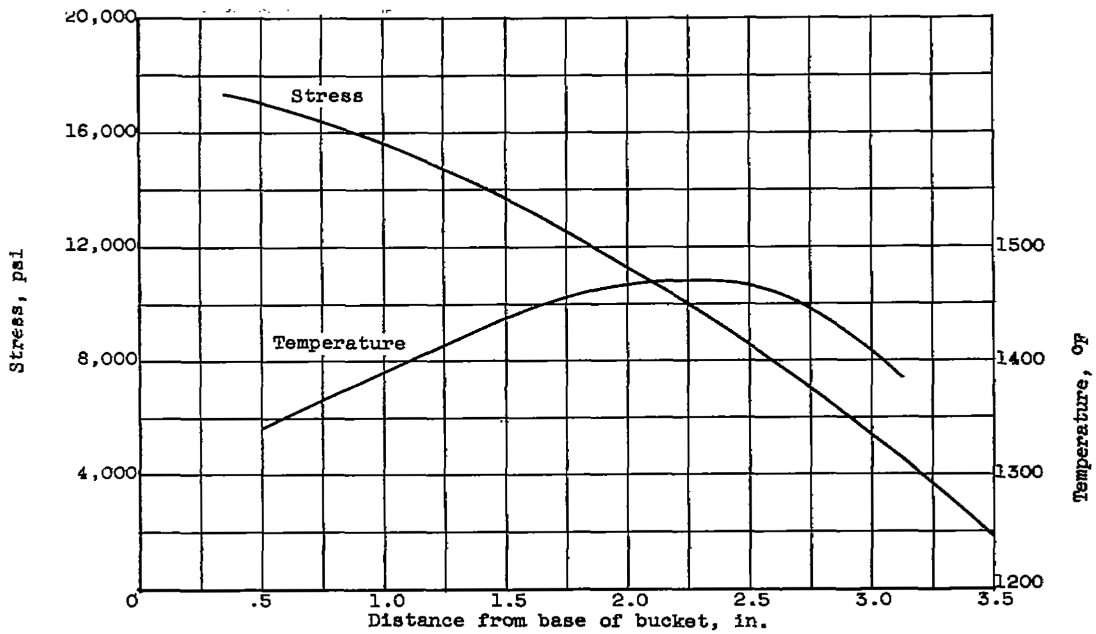


Figure 2. - Temperature and stress distribution. J47-25 turbine buckets operated at rated speed, 7950 rpm; tailpipe gas temperature, 1275° F; (S-816 density, 0.310 lb/cu in.).

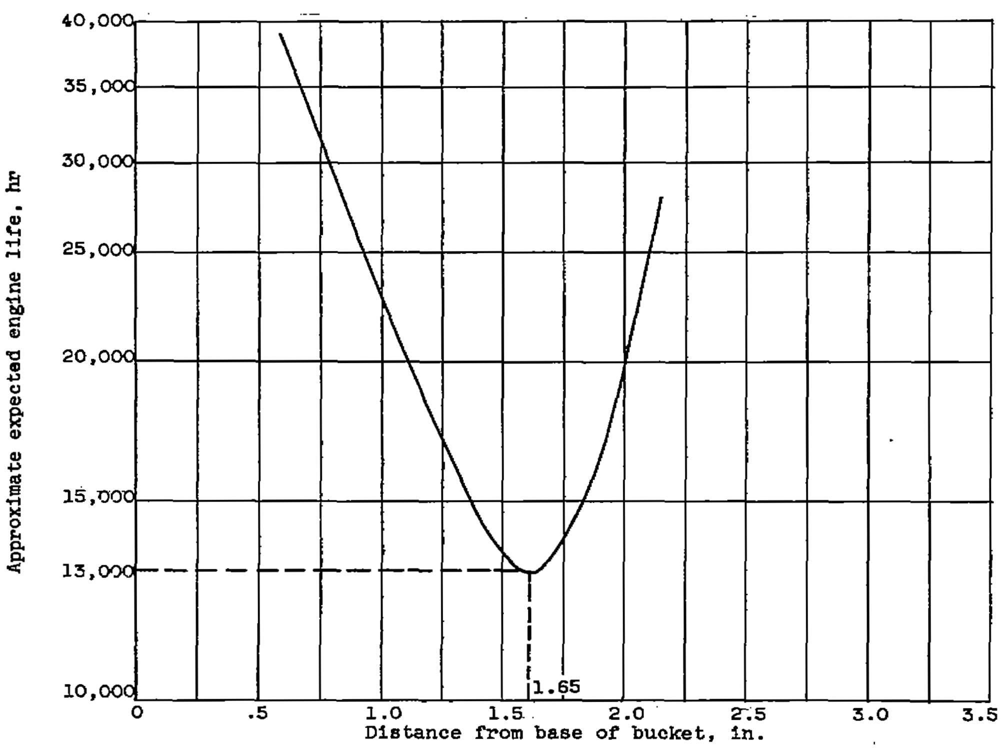
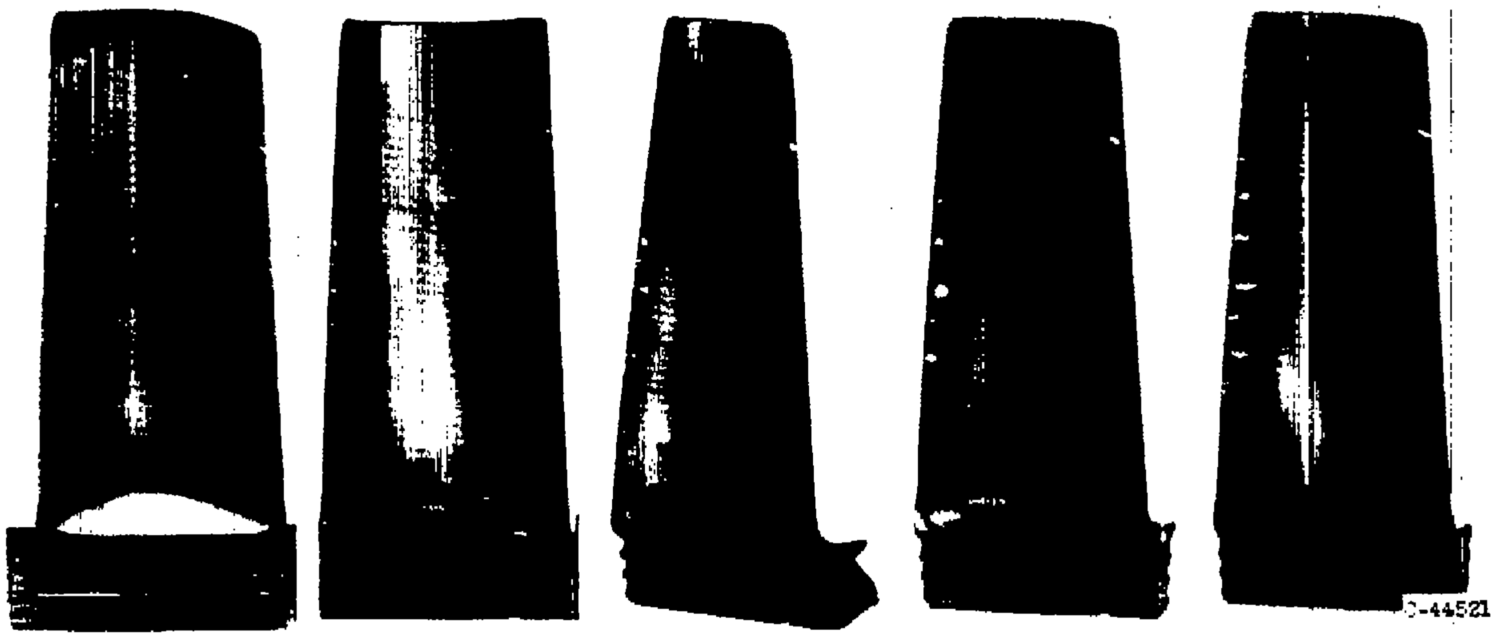


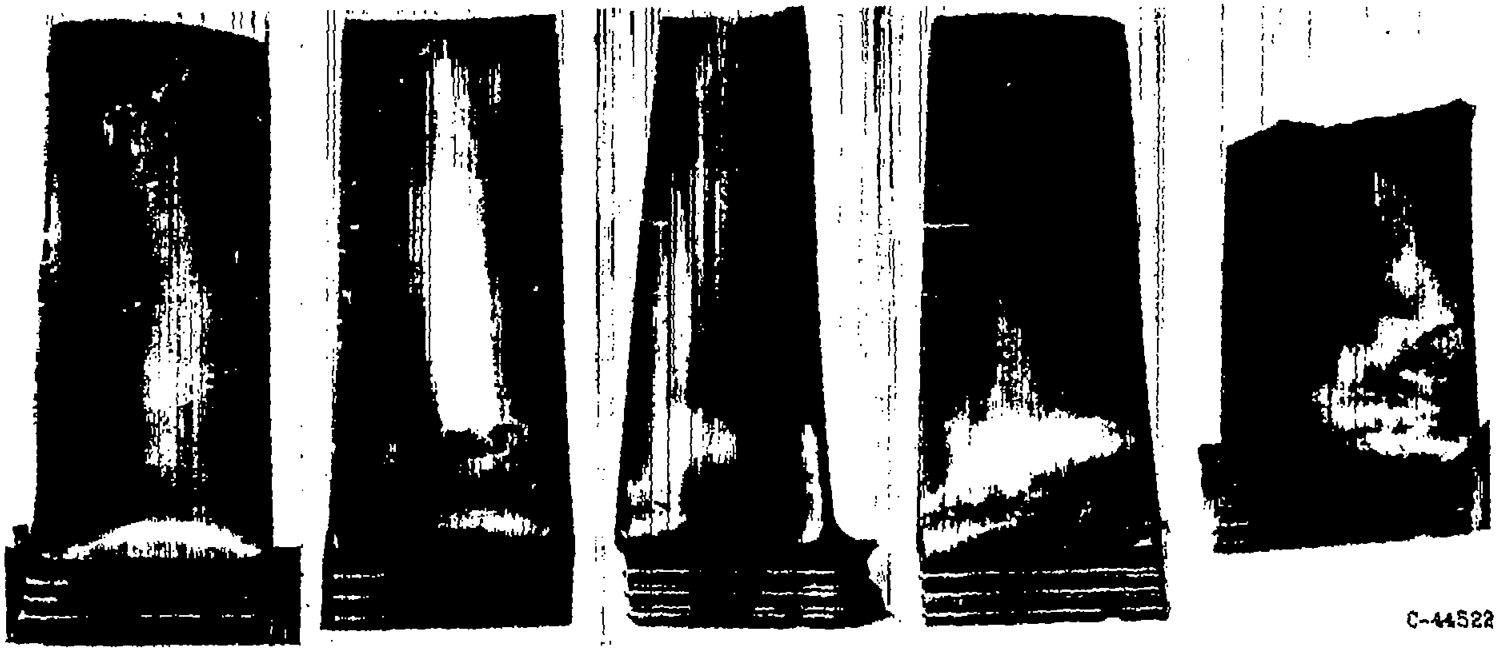
Figure 3. - Critical zone in an S-816, J-47-25 turbine bucket. Calculations based on General Electric data for 1300°, 1400°, and 1500° F. Simple interpolations were used for intermediate temperature.



Operation time, hr 55 139 175 278 457

(a) Inconel 550.

Figure 4. - Examples of crack propagation in turbine buckets.



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Operation time, hr	55	139	175	278	306

(b) S-816.

Figure 4. - Concluded. Examples of crack propagation in turbine bucket.

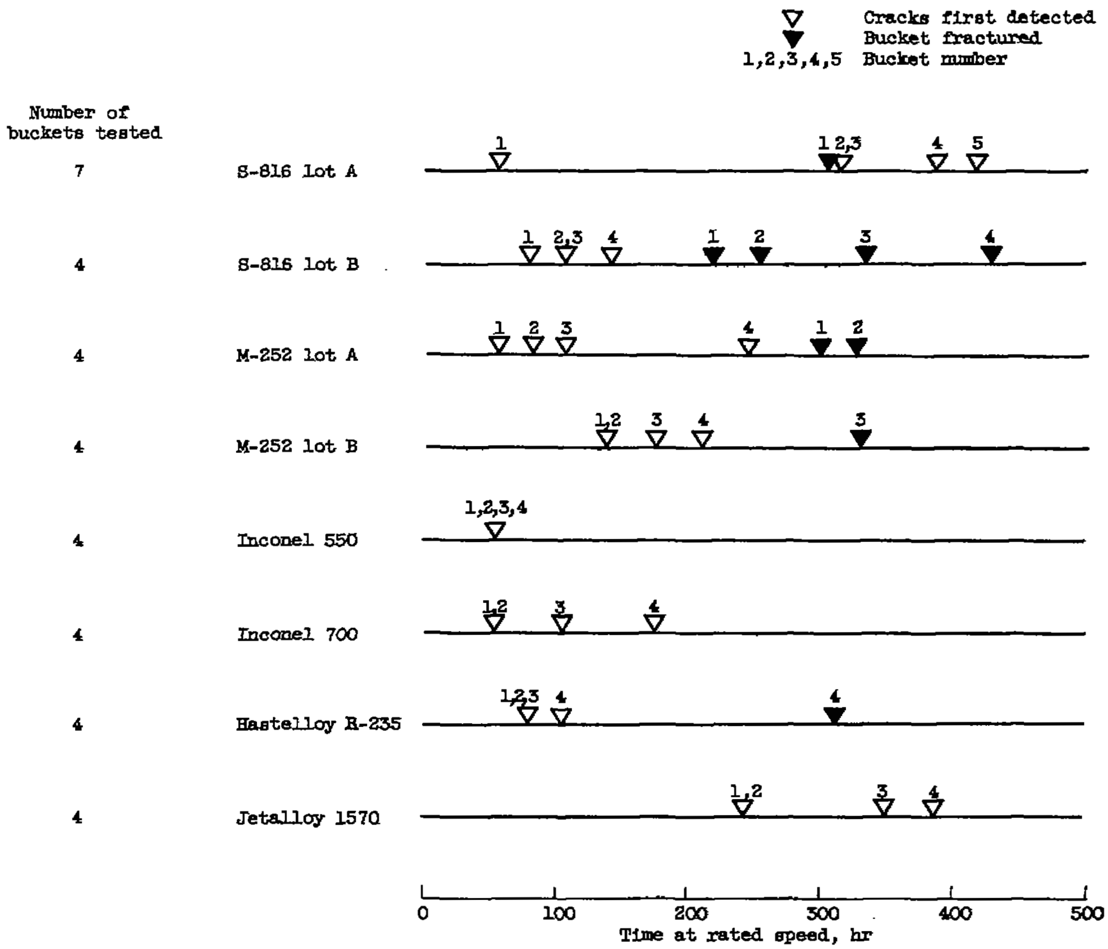
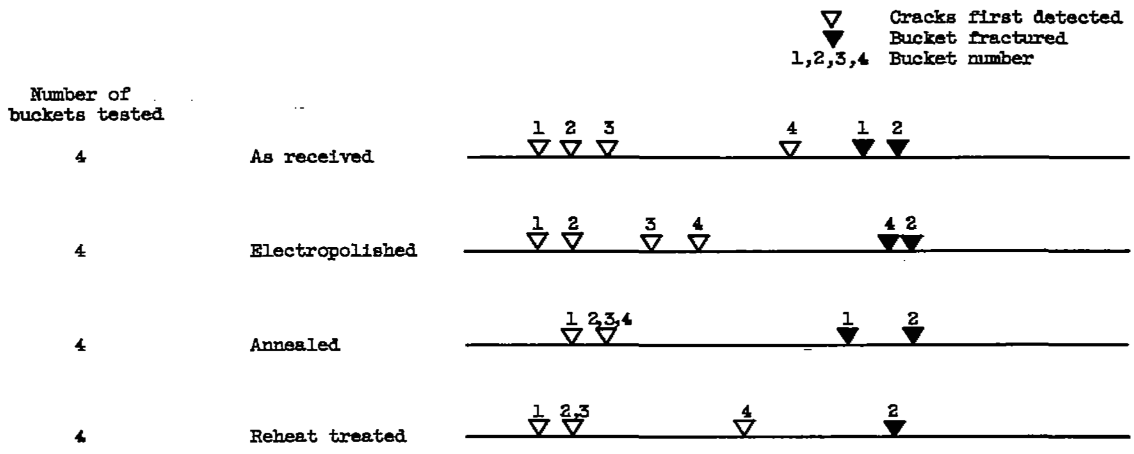
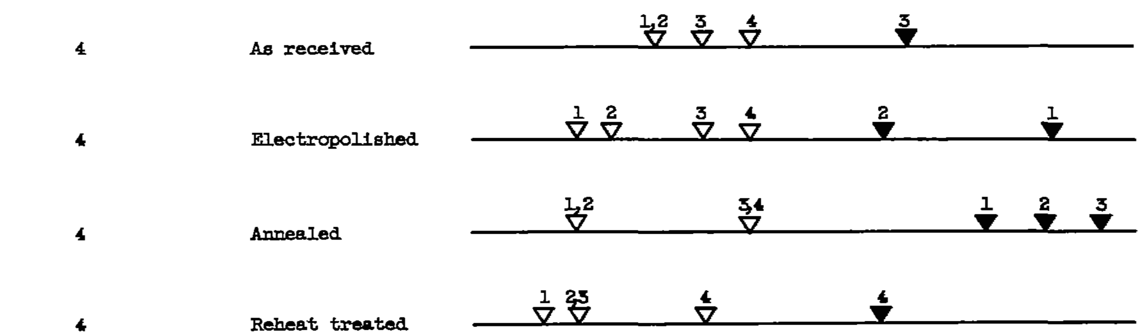


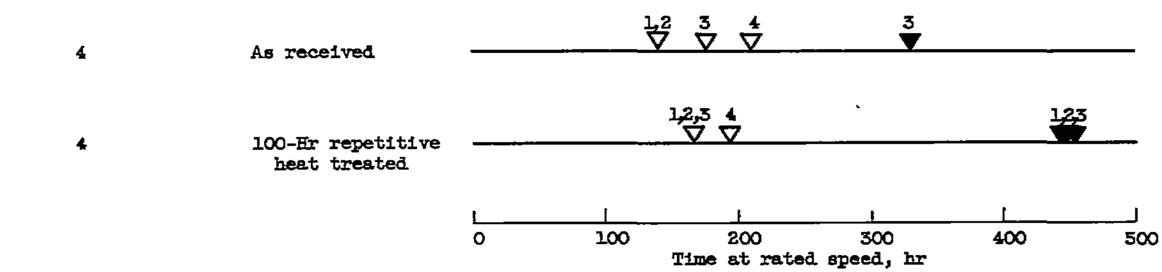
Figure 5. - Comparison of performance of as-received bucket materials. Test discontinued at 500 hours.



(a) M-252 lot A as-received and specially treated buckets.

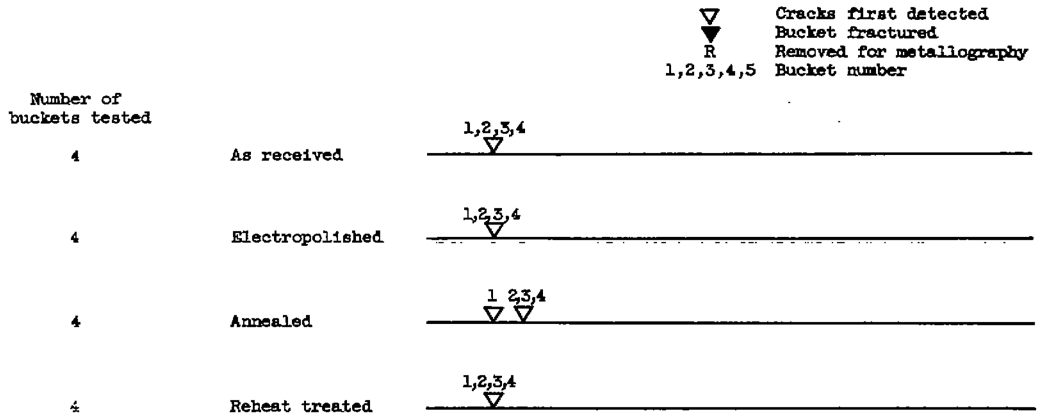


(b) M-252 lot B as-received and specially treated buckets.

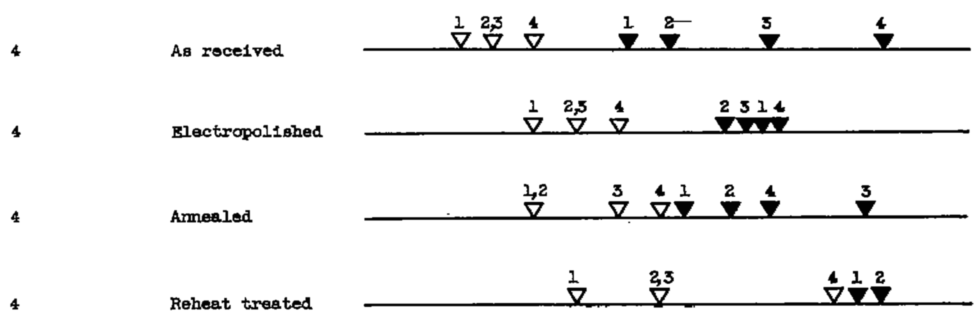


(c) M-252 lot B as-received and 100-hour, repetitively heat-treated buckets.

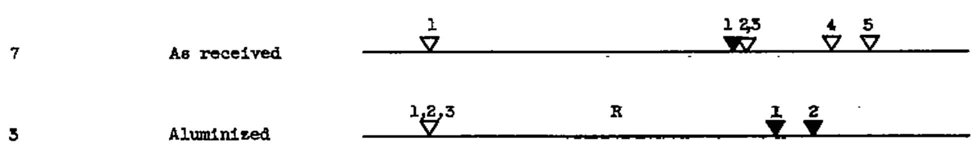
Figure 6. - Turbine bucket performance. Test discontinued at 500 hours.



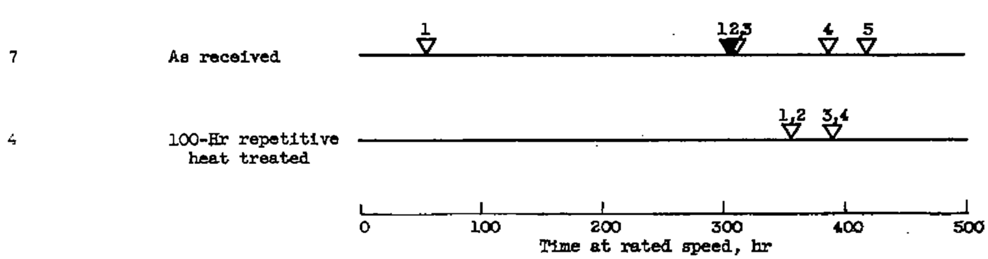
(d) Inconel 550 as-received and specially treated buckets.



(e) S-816 lot B as-received and specially treated buckets.

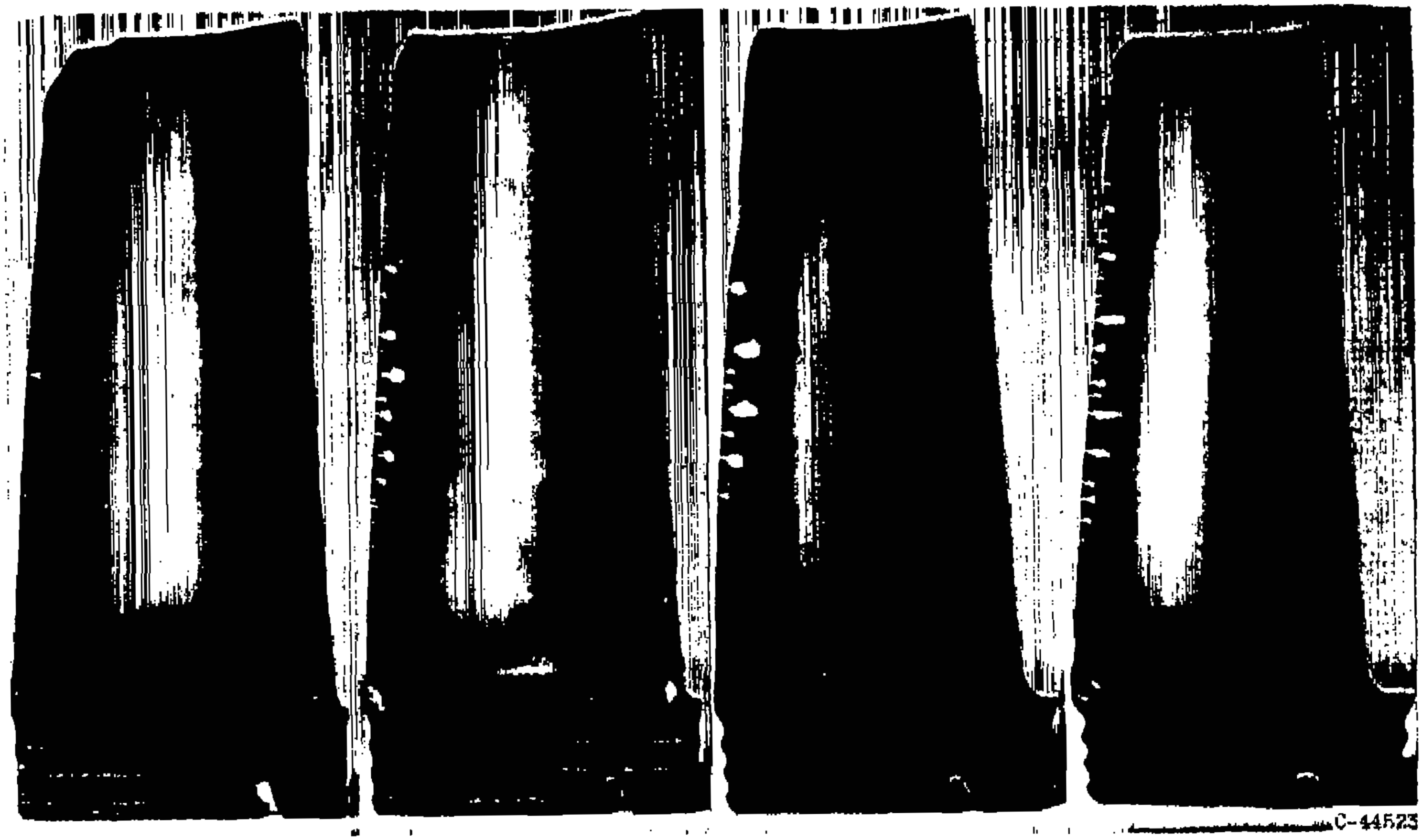


(f) S-816 lot A, as-received and aluminized buckets.



(g) S-816 lot A as-received and 100-hour, repetitive heat-treated buckets.

Figure 6. - Concluded. Turbine bucket performance. Test discontinued at 500 hours.



(a) S-816 lot A as-received bucket.

(b) M-252 lot A as-received bucket.

(c) M-252 lot B as-received bucket.

(d) Inconel 550 as-received bucket.

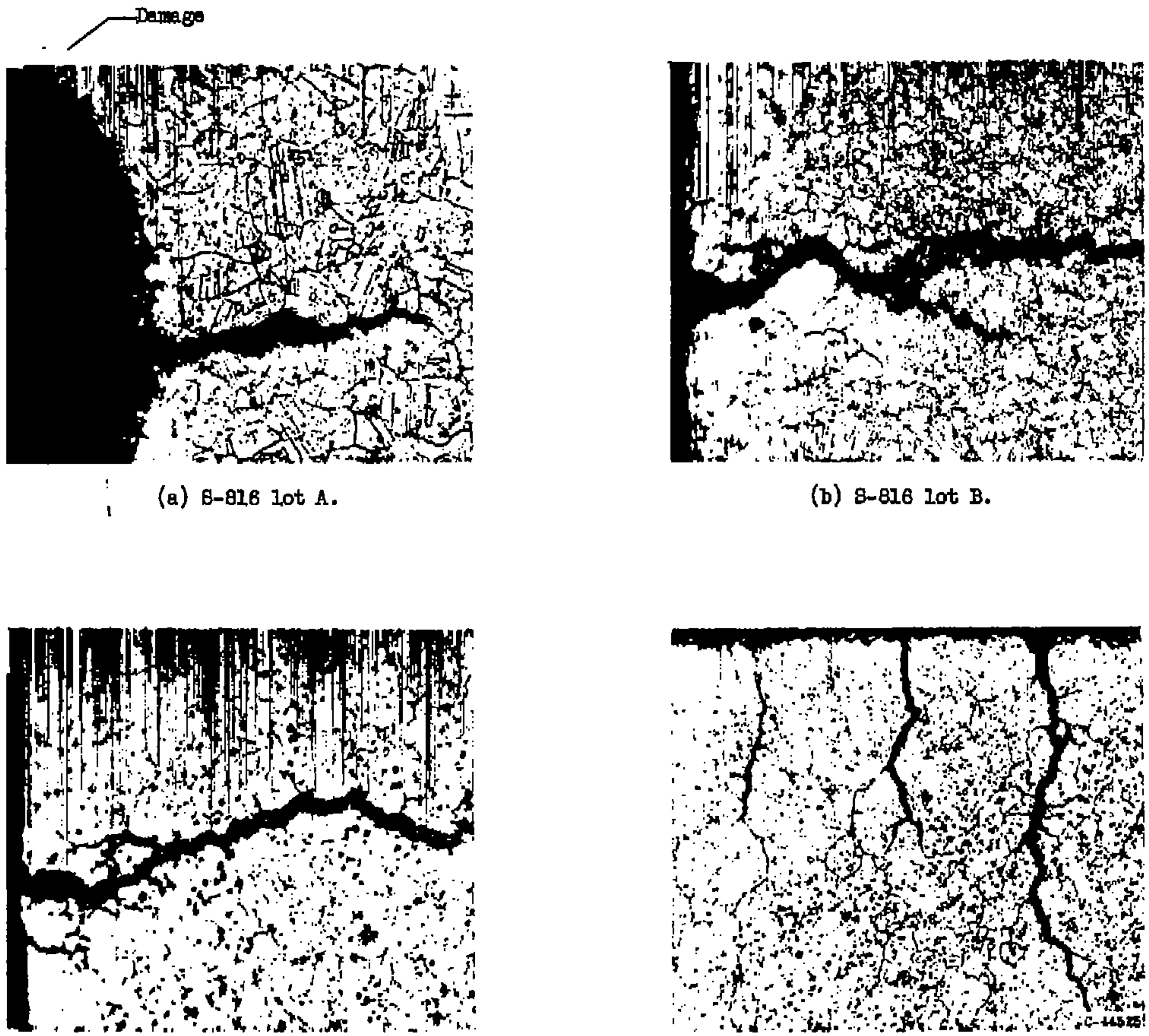
Figure 7. - Typical buckets that operated 500 hours at full power without fracturing. (Note leading-edge cracks.)

(e) Hastelloy R-235 as-received bucket.

(f) Inconel 700 as-received bucket.

(g) Jetalloy 1570 as-received bucket.

Figure 7. - Concluded. Typical buckets that operated 500 hours at full power without fracturing. (Note leading-edge cracks.)



(a) S-816 lot A.

(b) S-816 lot B.

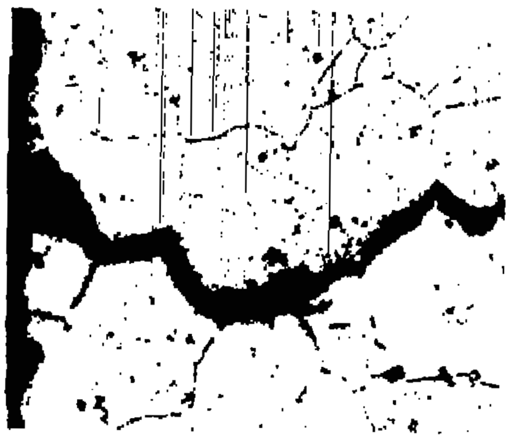
(c) M-252 lot A.

(d) M-252 lot B.

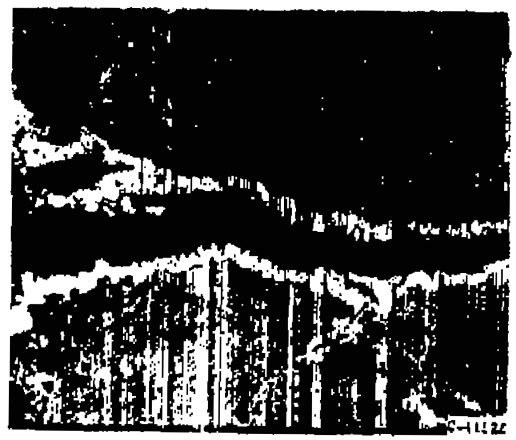
Figure 8. - Microphotographs of leading-edge cracks in buckets operated 500 hours without fracture. Eight different lots of material. X400.

(e) Inconel 550.

(f) Inconel 700.



(g) Hastelloy R-235.



(h) Jetalloy 1570.

Figure 8. - Concluded. Microphotographs of leading-edge cracks in buckets operated 500 hours without fracture. Eight different lots of material. X400.

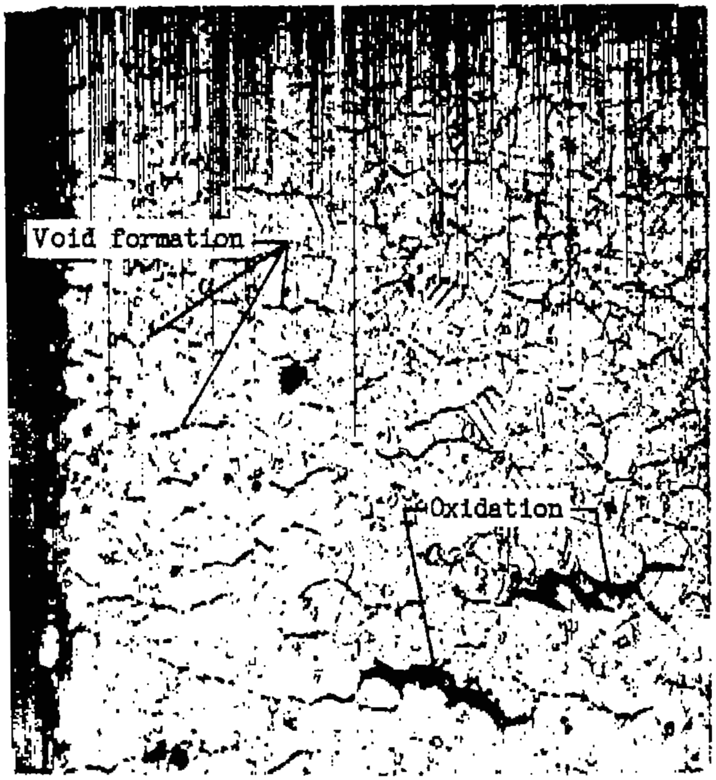
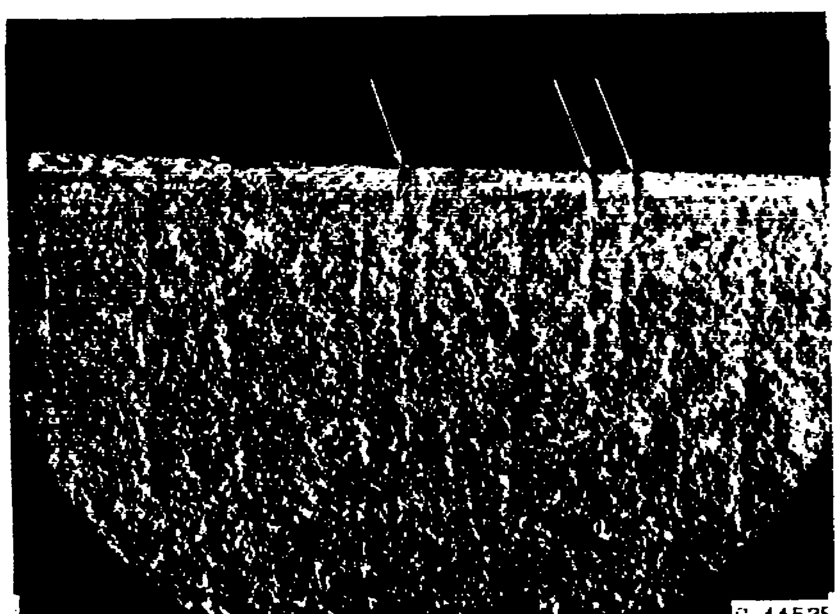


Figure 9. - Oxidation and void formation in grain boundaries of S-816 lot B bucket. X250.

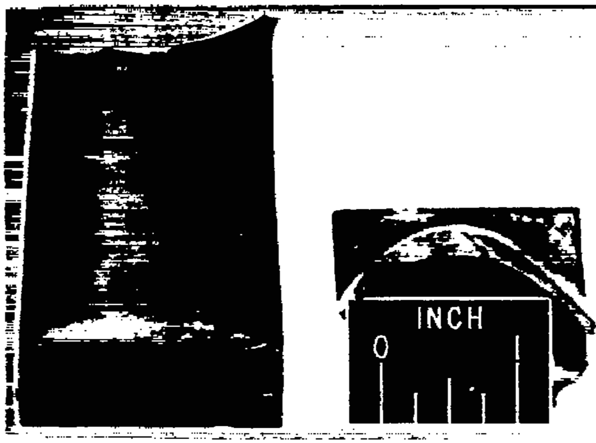
Figure 10. - Transgranular leading-edge crack in S-816 lot B bucket. X400.

(a) Microphotograph. X750.

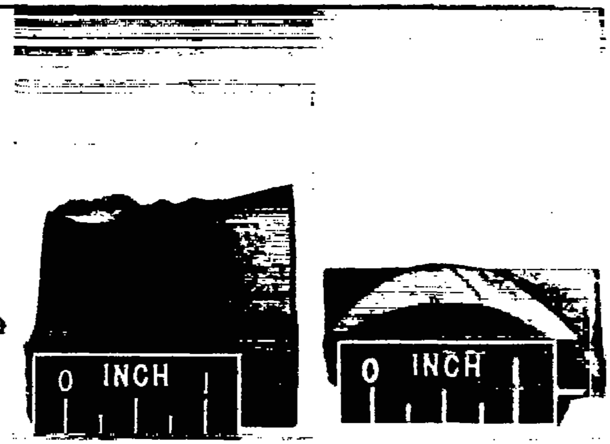


(b) 15X.

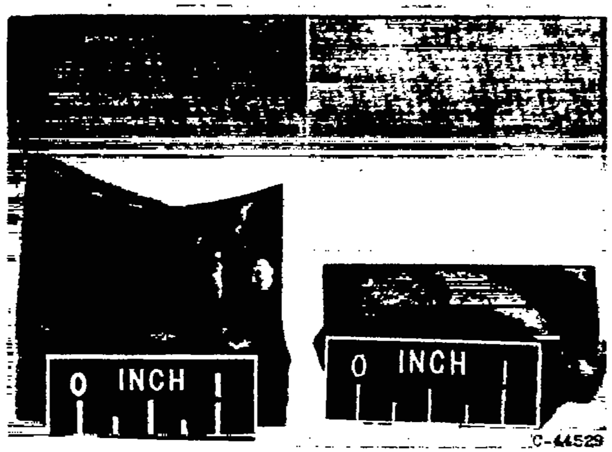
Figure 11. - Leading-edge cracks in aluminized S-816 Lot A bucket. Operation time, 244 hours.



(a) S-816 lot A as-received bucket. Fractured, 306 hours.

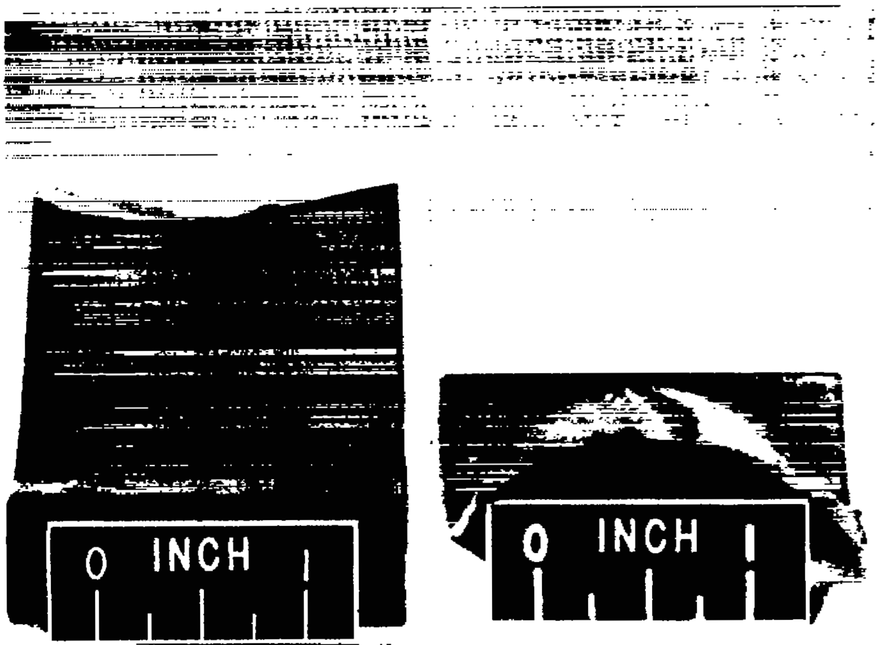


(b) S-816 lot B as-received bucket. Fractured, 335 hours.

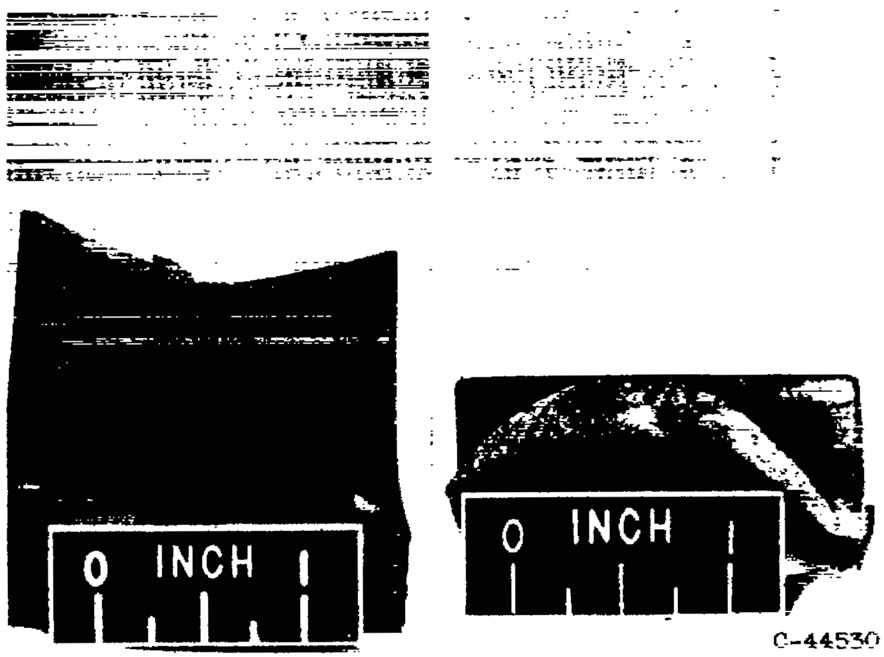


(c) M-252 lot A as-received bucket. Fractured, 300 hours.

Figure 12. - Typical bucket fractures resulting from engine operation.



(d) M-252 lot B as-received bucket. Fractured, 330 hours.



(e) Hastelloy R-235 as-received bucket. Fractured, 312 hours.

Figure 12. - Concluded. Typical bucket fractures resulting from engine operation.

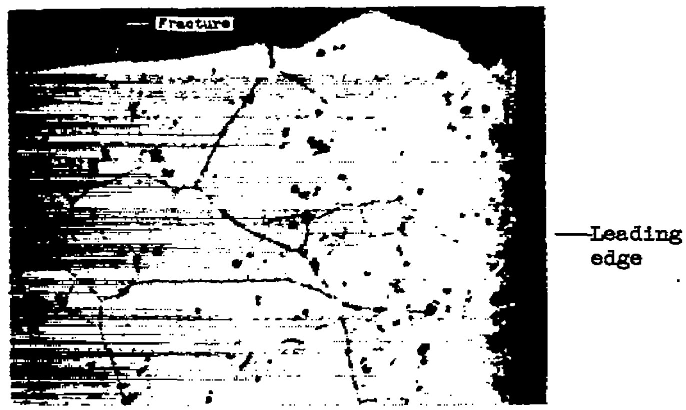


Figure 13. - Fracture origin in leading edge, Hastelloy R-235. Fractured, 312 hours.

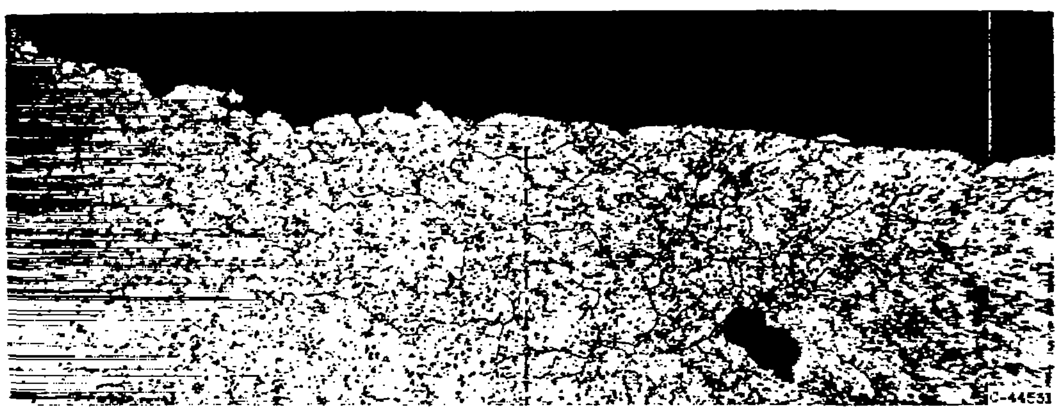


Figure 14. - Transition from intergranular to transgranular fracture for M-252.